A 2000 HOURS LIFETIME TEST RESULTS OF 1.3 kW T-100 ELECTRIC THRUSTER

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Abstract

The results of wear testing of stationary plasma Hall-type engine (SPHE) with 1.3 kW input power and T-100 index are reported. The duration of wear testing was 2000 hours long with more than 200 on-off cycles. The testing of T-100 has shown it's high reliability and stability of it's characteristics, and has confirmed the expectation of running more than 8000 hours endurance.

Introduction

The electrojet engine T-100 (1) that has been developed in NIITP is currently subject to a series of various tests, including endurance tests, which are necessary for preparation for on-board testing. The objectives of the endurance tests were: proving the engine's performance during long-time work, defining the variation of it's parameters with time, studying the erosion of engine's elements, studying the oscillations in the power circuit, measuring the electromagnetic radiation of the plasma in the engine, tuning the technique of accelerated endurance testing and preestimation of the engine operational Lifetime.

The 2000 hour long testing of T-100 engine has been carried out on two stands because of the regular maintenance of the stand equipment that has to be made once per 300 hours of work.

Parallel to engine testing, the endurance testing of it's major components, the cathode-neutralizer with wolfram-barium emitter developed exclusively for T-100, has been taken. The endurance testing of cathode neutralizers has been carried out on two sample cathodes working in two operating modes, such as continuous work with relatively rare switches on (during technological breaks) and the mode of sequential switching on and off.

Some specific features of the T-100 engine design are given below, as well as the description of the experimental stand and the results of the testing.

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The appearance of the WCN-5 cathode is shown in Figure 2. Cathode-neutralizer is a hollow cathode with gas pumped through, operating in the so-called mode of arc discharge with hot emitter. This mode provides the electron emission for neutralizing the volume charge of the ions with minimal power loss.

The cathode is designed for nominal current of 4.5 A. The gas (xenon) consumption under these conditions is 0.35 mg/s, and the decrease of voltage does not exceed 15-20 V. The emitter of the cathode has cylindrical shape with outer diameter 5 mm and is made of porous wolfram saturated with calcium-barium aluminate.

The working volume is a sphere of 2 mm diameter with output opening of 0.5 mm diameter.

The shell of the cathode works as starting electrode. It is made of molybdenum, and has an opening of 1 mm diameter. The starting electrode is electrically disconnected from the shell of the engine by an insulator. To initiate discharge between the emitter and starting electrode, a pulse voltage is applied with pulse frequency about several kHz. At the same time, the xenon consumption should be increased 3 to 5 times compared to nominal consumption rate for a short period of time. Time necessary to achieve the cathode working mode after the discharge initiation is less than 1 second. During this time, the emission element is heated by the discharge up to the working mode temperature, and then the consumption can be reduced to its nominal value. The advantages of starting the cathode without pre-heating the emission element are as follows: 1) much less xenon loss per 2 to 10 second startup, 2) versus 2 to 3 minutes of Xe flow before start up to conventional "hot" preheated cathode no need for heating element and its power supply (hence more reliability), and 3) less time required for preparing the engine to start. The disadvantages are the necessary increasing the amplitude of starting pulse voltage, and higher xenon flow for much shorter time during start.

Testing Equipment

Three vacuum test chambers (stands) have been used for testing. On two of them the T-100 engine have been tested, and the third one was used for testing two cathode-neutralizers.

The first stand for engine testing was vacuum chamber with diameter of 1600 mm and 3 m long (volume 10 cubic meters). The evaluation of the chamber is provided by ten high-vacuum-oil vapor pumps, each of them with performance 7000 liters per second (on air). That provided the xenon pressure of (5-7) x10^-5 (millimeters of mercury) in the vacuum chamber during the testing with nominal consumption.

The picture of the stand is shown in Figure 3.
Engine Test Stand

The stand has been equipped with pendulum-type thruster measuring unit, providing the measurement of thrust with error not exceeding 2%. The T-100 engine was installed on the mounting plate of the thruster measuring unit.

The second stand is a vacuum chamber with diameter of 1 m and 3.5 m long, equipped with four oil-vapor pumps, each of them with performance 7000 liters per second (on air), that provided the xenon pressure of 1...1.1x 10⁻⁴ (millimeters of mercury) in the vacuum chamber during the testing.

The electric power systems on both stands were similar to each other and consisted of two power sources: power source for discharge circuit and power source for discharge initiation. The source for discharge circuit allows one to vary the output voltage within the interval of 140 V to 450 V with the current up to 10A.

Cathode Test Stand

The power source for discharge initiation generates the pulses with amplitude of 1000 V and duration of 4 microseconds. Frequency of pulse sequence is 1.5 kHz, current in the pulse is up to 1 A.

Both stands have been provided with equipment capable of recording the oscillations in the power circuits in frequency range 30 Hz to 10 MHz. For recording the electromagnetic radiation of plasma stream, the equipment for measuring low-magnitude electromagnetic radiation in frequency range 1 to 13.5 GHz has been used on the stands.

The stand for separate testing the cathode-neutralizers is vacuum chamber with diameter of 1 m and 2.5 m long. It is equipped with oilless pumping system (turbomolecular pump with performance of 3500 liters per second). Inside the chamber, two working spaces have been mounted for two hollow cathode-neutralizers WCN-5.

In the continuous operating mode, the cathode was powered by DC source with steeply decreasing volt ampere characteristics (100-120 V in idle mode and 10-13 V with current of 4.5 A). A stainless plate was used to initiate the plasma stream.

The power supply of the discharge switch on/switch off mode was provided by special automatic control system allowing one to vary the time of cathode operation (in the range of 5 to 160 seconds), as well as the duration of the pause between switch-on (30 to 240 seconds).
The Results of T-100 Engine Testing

The testing has been carried out with the following nominal parameters values: discharge voltage $U=300\pm5\text{V}$, discharge current $I=4.4\pm0.05\text{A}$. The magnitude of discharge current was being corrected by means of measurement of anode consumption in the range of $4...4.4\text{mg/s}$. The cathode consumption was being maintained constant at $0.35\text{mg/s}$. During the testing, the coils of the engine's magnetic system were plugged serially into the discharge circuit.

Figure 4 shows how the thrust, pulse per unit, and efficiency of T-100 engine depend on the run time. During all the testing period the parameters of engine operation have been stable enough with average values: thrust, 8.2 gm; Specific pulse of 1700 sec; efficiency, 51%. No significant changes in engine characteristics have been observed even with relatively bad pollution of accelerating channel occurring during the operating on "oil" vacuum.

Maintaining the thermal regime of the engine appeared to be very important in the case of long operation time. It was found that the temperature of the rear wall of the engine did not exceed 200 C during it's work.

The amplitudes of voltage and current oscillations in the engine's power circuit considerably depend on the structure of the power supply circuit. During the resource tests, the engine has been connected to the power supply via special filter. The oscillations of voltage and current were measured at the filter output, directly on the discharge power circuit. The amplitudes of voltage and current oscillations practically did not change with the time of operation.

The voltage oscillations have been about 18 to 20 V, relative to the constant power supply voltage of 300 V. The oscillogram of the current oscillations is shown in Figure 5. The oscillations of current are of explicit non-harmonic kind, with steep increasing slope and relatively slow decreasing. The magnitude of the oscillations (peak-to-peak) was 6 to 8 A, and in certain cases reached 11 to 12 A.

The intensity of the electromagnetic radiation (EMR) of the electrojet engine T-100 plasma stream has been measured in the fixed frequencies of 1.42, 2.7 and 4.5 GHZ, that has been selected based on the results of pre-testing studies as the most intensive in the range of 1 to 7 GHZ. EMR of the plasma stream of the electrojet engine is non-constant, being the series of pulses about 100 microseconds long with random intervals of 1 to 5 milliseconds. In the peak moments, the intensity of radiation is 3 to 5 orders of magnitude higher than the thermal level.

The results of the measurements of the T-100 engine plasma stream electromagnetic radiation intensity relative to operation time are shown in Figure 6. One should note the peak of radiation about 900-1200 hours and the following decrease until 2000 hours. The reasons of such behavior of the radiation are not yet clear and are subject to further studies.

The outer shell of the accelerating channel of the anode unit is most affected by erosion. The degree of erosion of the outer shell was measured in 8 longitudinal cross-sections of the
chamber, selected at uniform angular interval. The erosion of the inner wall of the insulator in T-100 engine is significantly less due to selected design of accelerating channel and magnetic system. The pictures of the engine taken after 1127, 1392 and 2003 hours of engine operation are given in Figure 7-9. The measurements of erosion depending on the engine operation time are given in Figure 10. Based on the erosion measurements, the estimates of the expected erosion and engine resource have been made. The estimates are shown in Figure 10. According to the estimates, that with the insulator shell 11 mm thick at the channel output, the edge of the T-100 engine outer shell could erode to the metal magnetic ring after 8000 hours. More than 600 hours tests of other sample T-100 engine, taken somewhat later in JPL, confirmed that the estimated endurance of the shell of accelerating channel is about 8000 hours.

The other component that appeared to be subject to erosion, was the shell of the cathodeneutralizer. The degree of the erosion of the outer surface of it’s shell depends on cathode’s position relative to the plasma stream ejected by the engine. In order achieve the required endurance, the cathode has been displaced aside from the plasma stream, and a protecting cover has been installed over it’s shell. These measurements provide assurance that the endurance of the cathode shell will also reach 8000 hours.

The Results of Separate Testing of the Cathode-Neutralizers

The separate testing of the WCN-5 cathodes have shown that the operability on the cathode is considerably affected by the purity of the used gas (xenon). The first sample was reached approximately after 300-400 hours of testing. The cathode starting was troubled, the discharge...voltage, energy emission and temperature of emission element increased.

The estimates show that with xenon purity (Standard 10219-77) with 0.003 % of admixtures, the desired endurance (5000...6000 hours) of the cathode can be reached only with additional purification of xenon by getters having absorption capability an order of magnitude higher than that of getters built in the WCN-5 cathode. With highea purity xenon availible in the U.S. the need for additional Filter might be Eliminated.

The cathode testing has been continued with additional xenon purification.

The given parameters of cathode operation in continuous mode are the consumption of gas m=0.35...0.4 mg/s and the discharge current I - 4.5 A. The recorded parameter is the discharge... voltage between cathode and imitator of plasma stream. Up to the current moment, the cathode has been working in continuous mode (interrupted for technical breaks only) for more than 1500 hours without any negative effects on it’s characteristics. The tests are to be held until the cathode is out.

The cathode-neutralizer WCN-5 operation in switch on/off mode has run more than 20,000 on/off cycles up to the present time. In this case, no negative effects on it’s parameter have been observed either. Therefore, the assumptions that the cathode starting without
Specific features of the T-100 engine design

The appearance of the T-100 engine that has been subject to 2000 hour testing is shown in Figure 1 that has been taken prior to the start of testing. The engine has the following major characteristics.

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<table>
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<td>Electric power consumption</td>
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<tr>
<td>Voltage for main discharge</td>
<td>DC 300 V</td>
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<td>Gas (high purity xenon) consumption</td>
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The accelerating channel (nozzle) of the engine has the form of circular slot 15 mm wide. The channel is placed between the poles of magnetic system inducing a radial magnetic field. The outer diameter of the channel is 100 mm.

The specific feature of this engine is that the ion stream is being focused onto the axis of accelerating channel in the acceleration zone. This is achieved by the geometrical design of the channel and by the configuration of the magnetic field: the outer insulator shell of the channel is longer than the inner, and the outer magnetic pole is placed downstream, in relation to the inner one. The magnetic shunts are used, conventionally, for achieving necessary spatial distribution of the magnetic field in the channel.

Focusing the ions onto the axis allows a reduction in the wear of the outer shell of the channel and to increase it’s resource. Since the inner shell is shorter than the outer, it is essentially not subject to the eroding effect of accelerated ions.

The gas-distributing anode is placed deep in the accelerating channel, 30 mm from the output plane of the engine.

The magnetic system consists of magnetic poles, magnetic cables and five induction coils, that can be either plugged (in series way) into the male discharge power circuit, or to be powered by separate source. During the testing, the coils were plugged in the series main discharge power circuit.

The T-100 engine has two (one for emergency) cathode-neutralizers WCN-5, placed near the output plane of the accelerating channel.

**Cathode-Neutralizer WCN-5**

The cathode-neutralizer provides the neutralizing of the volume charge of the ion stream, and is also used for starting the engine. This component is one of the most important components of the engine, while allowing separate adjusting which imposes considerably less strict requirements on the testing equipment. That is why the testing of cathode-neutralizers in two modes mentioned above have been taken parallel to engine testing.
The cathode-neutralizer VCN-5 operation in switch on/off mode has run more than 20,000 on/off cycles up to the present time. In this case, no negative effects on its parameter have been observed either. Therefore, the assumptions that the cathode starting without pre-heating could cause over-erosion and impose negative effects upon its parameters, are unlikely to come true. These testings are going to be carried on further.

Conclusion

The 2000 hour long resource testing of T-100 engine have confirmed the decisions concerning technical design of the engine components to be right, and have also allowed to introduce a number of improvements, increasing its endurance and reliability. During all 2000 hours period of operation, the major parameters of the engine remained stable: efficiency 50-52 %, thrust-80 mN with 300 voltage, xenon consumption 5.1 mg/s and power consumption 1.3 kW.

The studies of the erosion of T-100 accelerating channel have shown that estimated resource of the anode unit of the engine is 8000 hours or more.

The resource testing of non pre-heated cathode-neutralizers WCN-5 have shown that, if the used gas (xenon) meets the required purity conditions, the cathodes with wolfram-barium emitters have sufficient resource and reliability. The 20000 switch on/off cycles of cathode operation show that starting the cathode without pre-heating Wolfram-barium emitter is not dangerous for cathode operation parameters.

References


Fig. 1. The engine T-100 before beginning of tests
Fig. 2. Cathode-accelerator of the engine T-100

Fig. 3. Equipment for producing life time tests of the engine T-100

Fig. 4. Stability of thrust specific impulse in vacuum, efficiency with time

Fig. 5. Oscillogram of discharge current oscillations $I_d$:
$U_{op}=296$ V, $I_{op}=4.44$ A, $m_0=4.3$ mg/s,
$m_0=0.35$ mg/s, $P = 8 \times 10^{-5}$ Torr

Fig. 6. Results of individual measurements of electromagnetic interference intensity of different stages of SPT-100 testing, Operation mode: 4.42-4.45 A

298-303 V
Fig. 7. The T-100 engine after 1127 hours of testing.

Fig. 8. The T-100 engine after 1392 hours of testing.

Fig. 9. The T-100 engine after 2003 hours of testing.

Fig. 10. Time dependence of erosion of T-100 and M-100 thrusters outer insulators.

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T-100

M-100